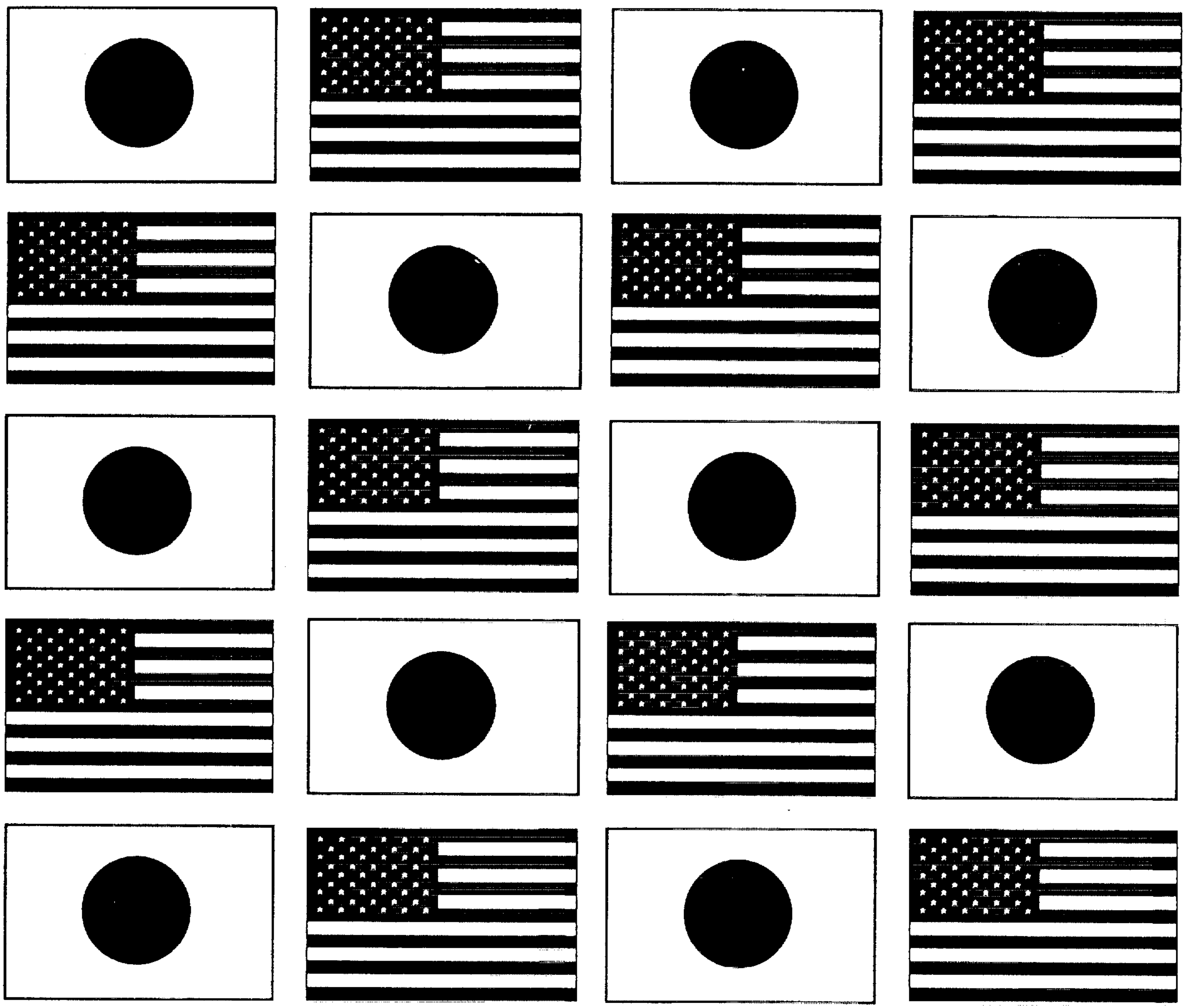
# Wind and Seismic Effects

## Proceedings of the 30th Joint Meeting

NIST SP 931



**U.S. DEPARTMENT OF COMMERCE**
**Technology Administration**
**National Institute of Standards and Technology**

# Wind and Seismic Effects

## NIST SP 931

PROCEEDINGS OF THE 30TH JOINT MEETING OF THE U.S.-JAPAN COOPERATIVE PROGRAM IN NATURAL RESOURCES PANEL ON WIND AND SEISMIC EFFECTS

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# EARTHQUAKE ENGINEERING

# DRAFT MANUAL FOR SEISMIC ISOLATION DESIGN OF UNDERGROUND STRUCTURES

by

Shigeki UNJOH[1], Jun-ichi HOSHIKUMA[2], Kazuhiro NAGAYA[2] and Kazuhiko MURAI[3]

## ABSTRACT

Public Works Research Institute has conducted 3-year joint research program on seismic isolation systems for underground structures to improve the structural performance and the safety during earthquakes. This project has been made through the joint research program between Public Works Research Institute, Public Works Research Center and 17 private companies. Developed seismic isolation systems for the underground structures are made by constructing the isolation materials with low-shear modulus around the underground structures to absorb the effect of ground deformation. Five kinds of seismic isolation materials have been developed and the analysis and design methods for the underground structures with the seismic isolation systems have been also studied and developed. The final accomplishment is complied as a "Draft Manual for Seismic Isolation Design of Underground Structures" in March 1998.

*KEY WORDS : Seismic Design*
*Underground Structure*
*Seismic Isolation*
*Seismic Isolation Material*
*Seismic Isolation Design*
*Design Manual*

## 1. INTRODUCTION

Underground structures such as tunnels and pipelines are generally affected by the displacement and deformation of the surrounding ground during earthquakes. In general, therefore, the underground structures are less influenced by the effect of earthquakes than the structures on the ground in which the earthquake response is amplified through the structures.

On the other hand, the underground has recently been starting to be developed and to be densely used especially in urban areas. The underground structures are often required to be constructed at the sites where the effect of earthquake becomes critical in the design, such as the sites with soft soil conditions, the sites where the ground condition is drastically changing, and the sites where structures with different vibrational characteristics are constructed closely or jointly.

During the 1995 Hyogo-ken-nanbu Earthquake, the damage to the underground structures were relatively slight comparing the structures on the ground such as buildings and bridges. However, some of the underground structures such as subway station were damaged destructively. At the Daikai-Station of the Kobe High Speed Train, the RC columns were failed in shear and the upper slab was settled.

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The damage to sewage systems such as cracks and dislodgement of pipes were also found. The Public Works Research Institute has been studied and developed the seismic isolation systems for the underground structures to improve the seismic performance and the safety by constructing the isolation materials with low-shear modulus surrounding the underground structures. The isolation materials absorb the deformation of the ground during the earthquakes. This study was made through the joint research program between Public Works Research Institute, Public Works Research Center, and 17 private companies including material makers, general contractors, design consulting firms.

In the Joint research program, major objectives of the research and development are as follows:
1) Development of Isolation Materials Applicable for the Seismic Isolation Systems
2) Construction Methods of Seismic Isolation Materials
3) Design Methods for Underground Structures with Seismic Isolation Systems

The final accomplishments of the research and development is compiled as the "Draft Manual of Seismic isolation design for Underground Structures" in March 1998.

This paper presents the concept of the seismic isolation systems for the underground structures and the outline of the draft design manual.

## 2. SEISMIC ISOLATION SYSTEMS FOR UNDERGROUND STRUCTURES

### 2.1 Concept of Seismic Isolation Systems

In general, underground structures are subjected to the deformation through the interaction between the ground and the structures. Therefore, when the stiffness of the structures are increased, the flexibility of the structures is decreased then the section force developed against the same deformation is increased. Hence, the design to increase the section or number of reinforcing bars to ensure the earthquake force developed like usual structures is not effective in general. In this case, it is effective to isolate the structures from the deformation of the ground.

There are several ways to decrease the effect of ground deformation to be transmit to the underground structures. Major ways are the followings :
1) To make the underground structures flexible by decreasing the stiffness
2) To decrease the effect of ground deformation to be transmitted to the underground structures

The usual way, which has been employed for actual submerged tunnels and shield tunnels and common utility ducts, is the above 1) using flexible joints. When the stiffness of the joints are decreased, the ground deformation is absorbed at the joints and the section force of the structures is decreased. However, when the displacement developed at the joints becomes excessive, there are cases in which such excessive displacement is not acceptable or the special water-proof joints are required depending on the performance level required to the structures during large earthquakes.

On the other hand, the above 2) includes the methods in which the seismic isolation layer consisted of the materials with low shear modulus comparing the surrounding soils are constructed around the structures as shown in **Fig.1**. Since the shear deformation of the ground is absorbed by the seismic isolation layer, the excessive displacement, which may be developed at the specific joints, is prevented by this methods. Furthermore, since the ground deformation is absorbed, the isolation layer is effective to earthquake ground deformation both in the longitudinal and transverse directions.

Here, the method to decrease the effect of earthquakes by constructing the seismic isolation layer around the underground structures is defined as "Seismic Isolation Systems for Underground Structures".

**2.2 Application of Seismic Isolation Systems**

Th effect of earthquake is generally large for the underground structures under the following conditions based on the past earthquake damage experiences.

1) Boundary section where the ground conditions are critically changed

The effect of earthquakes on the underground structures becomes large at the sites where the ground condition is changing from stiff ground to soft ground, or from cut ground to embanked ground. The deformation and the strain is concentrated at the boundary of the such sections with the change of ground conditions.

2) Connection section of two different structures

The deformation is concentrated at the connection section between shaft and tunnels, or junction sections, by the difference of the vibrational characteristics of two adjacent structures.

Therefore, the application of the seismic isolation systems is effective such boundary sections with different ground conditions or different structural conditions as shown in **Fig.2**. The concentration of the deformation and the strain is absorbed by the seismic isolation layer and the seismic performance of the underground structures can be improved.

Also, the transmission of shear deformation can be decreased by the seismic isolation layer, the effect of earthquakes is decreased for the transverse direction of the structures with wide section in which the surrounding shear stress is critical in the seismic design.

Furthermore, when it is required to prevent water from coming in the structure depending on the required performance of the structures, the application of the seismic isolation layer with a water-proof function is effective both for the increase of the earthquake resistant performance and the water-proof performance.

**2.3 Seismic Isolation Materials**

Seismic isolation materials applicable to the underground structures are required to have the performances of seismic isolation functions and the function as the backfill materials. The development of the seismic isolation materials have been made for the shield-driving tunnels and the open-cut type tunnels. The required performances are as follows:

1) Low shear modulus and high shear deformability
2) High durability, long-term stability, and small volumetric changes
3) High constructionablity (for example for shield-driving tunnels : transportability by pumping in a liquid state and high filling-up performance
4) Watertightness
5) No dilution by ground water
6) No contaminants

Based on the above required performances, in the joint research program, 5 kinds of the seismic isolation materials were developed as shown in **Table 1**. The material characteristics including mechanical one, such as shear modulus, durability, watertightness, creep, and constructionablity were tasted using developed materials.

**Fig.3** shows examples of the mechanical properties of the developed materials obtained through the hollow cylindrical cyclic shear tests. The all materials were tested by the same testing methods.

To simulate the actual condition in the tests, the surface soil layer with about 3m are assumed for the open-cut type tunnels. And for the shield driving tunnels, the surface layer with about 20 m was assumed. Then the confined pressures were selected as 0.5, 1.5 and 3.5 $kgf/cm^2$. The cyclic loading rate is assumed as 1 Hz considering the natural period of the surface layer. The strain range tested was assumed up to 10% considering the large deformation during the large earthquakes based on the analytical results.

**Fig.3** shows that the shear modulus and damping ratio for Urethan-based material, Silicon-based material and Liquid Rubber material are almost constant in the range of the strain tested. And the confinement dependency was not found.

On the other hand, Asphalt-based material has the strain dependency in which when the strain increases the shear modulus decreases and the damping increases. The confinement dependency is found at the small strain range but is not remarkable.

For Precast Rubber Panel, the strain dependency and confinement dependency are found. Since the precast rubber panel is made by binding the rubber tips by resin, the precast rubber panel has the void inside the panel. The strain dependency is developed by the resin characteristics is changed in the high strain range then the shear modulus decreases.

Seismic isolation design of the underground structures has to be made based on the material characteristics as above mentioned. Some materials have other dynamic characteristics such as velocity dependency. They are also obtained through the necessary tests.

### 2.4 Construction Methods

**Fig.4** shows the outline of the construction methods of seismic isolation materials. For the shield-driving tunnels, the same construction methods of the backfill to the tale void is applicable. The materials are injected to the tale void from the inside of the tunnels and the seismic isolation layer has constructed around the structures. To prevent the inflow of the isolation materials toward the shield machine and to construct seismic isolation layer certainly in the tale void, the shield machine requires the inflow prevention devices but not important remodeling. For the open-cut type tunnels, the seismic isolation layer can be constructed with the construction of the tunnels. In the joint research project, both construction methods are verified through the construction tests of the seismic isolation layer.

## 3. VERIFICATION TESTS OF THE EFFECTIVENESS OF SEISMIC ISOLATION SYSTEMS

### 3.1 Test Models

To verify the effectiveness of the seismic isolation systems, the model tests were made using large shake table at the Public Works research Institute.

**Fig. 5** shows the scale of the model. Tunnel is assumed to be constructed at the change section of ground conditions. The tunnel was the almost 1/70 size of actual structures with a diameter of 70mm and the thickness of 2mm. The ground was made of Silicon where the soft soil was assumed to have the shear modulus of $1kgf/cm^2$, and the stiff soil was assumed to have the $20kgf/cm^2$. Seismic isolation layer was assumed to have the thickness 10mm and the shear modulus of $0.05kgf/cm^2$.

The model was subjected to the sinusoidal ground motion and the random earthquake ground motion. Since the natural frequency of the model was 6.5Hz, the sinusoidal wave with the natural frequency of the ground was input to the shake table.

### 3.2 Test Results

**Fig. 6** shows the typical test results. In the right side section where the ground condition is changed, the seismic isolation layer is constructed. The strain in the tunnels in the longitudinal direction developed at the change section of the ground conditions was decreased by 30% by employing the isolation layers. This was the almost expected effectiveness through the analysis.

## 4. DRAFT MANUAL FOR SEISMIC ISOLATION DESIGN OF UNDERGROUND STRUCTURES

### 4.1 Table of Contents

The draft manual consists of 9 chapters, 4 design examples and the 12 reference materials. The table of contents is as follows.


1. General
   - 1.1 Scope
   - 1.2 Definition of Terms
   - 1.3 Symbols
2. Basic Principle of Seismic Isolation Design for Underground Structures
3. Design Earthquake Ground Motion and Design Ground Displacement
   - 3.1 General
   - 3.2 Design Ground Displacement during Earthquakes
   - 3.3 Dynamic Soil Properties
   - 3.4 Design Earthquake Response Spectrum
   - 3.5 Input Ground Motion for Dynamic Analysis
4. Seismic Design of Underground Structures in Transverse Direction
   - 4.1 General
   - 4.2 Horizontal Ground Displacement during Earthquakes
   - 4.3 Static Analysis Methods of Underground Structures in Transverse Direction
     - 4.3.1 General
     - 4.3.2 Response Inertia Force Methods
     - 4.4.3 Other Static Analysis Methods
   - 4.4 Model of Underground Structures in Transverse Direction
     - 4.4.1 Model of Shield Driving Tunnel
     - 4.4.2 Model of Open-Cut Type Tunnel
   - 4.5 Evaluation of Safety
   - 4.6 Check of Safety by Dynamic analysis Methods
     - 4.6.1 General
     - 4.6.2 Analytical Model
     - 4.6.3 Evaluation of Safety
5. Seismic Design of Underground Structures in Longitudinal Direction
   - 5.1 General
   - 5.2 Horizontal Ground Displacement during Earthquake
   - 5.3 Static Analysis Methods of Underground Structures in Longitudinal Direction
     - 5.3.1 General
     - 5.3.2 Analysis Methods using Beam-Mass Model
     - 5.3.3 Analysis Methods using Axisymnmentrilc Model
     - 5.3.4 Analysis Methods using Simplified 3-Dimensional FEM Model
     - 5.3.5 Analysis Methods using 3-Dimensional FEM Model
   - 5.4 Model of Underground Structures in Transverse Direction
     - 5.4.1 Model of Shield Driven Tunnel
     - 5.4.2 Model of Open-Cut Type Tunnel
   - 5.5 Evaluation of Safety
   - 5.6 Check of Safety by Dynamic analysis Methods
     - 5.6.1 General
     - 5.6.2 Analytical Model
     - 5.6.3 Evaluation of Safety
6. Seismic Design of Connection Section between Shaft and Tunnel

6.1 General
6.2 Horizontal Ground Displacement during Earthquake
6.3 Static Analysis Methods of Connection Section between Underground Structures
6.4 Model of Shaft and Underground Structures
6.5 Evaluation of Safety
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7.2 Asphalt-based Material
7.2.1 General
7.2.2 Material Properties
7.3 Urethan-based Material
7.3.1 General
7.3.2 Material Properties
7.4 Silicon-based Material
7.4.1 General
7.4.2 Material Properties
7.5 Liquid Rubber Material
7.5.1 General
7.5.2 Material Properties
7.6 Precast Rubber Panel Material
7.6.1 General
7.6.2 Material Properties
8. Design of Seismically Isolated Tunnels against Usual Loads

Design Examples
1. Design Example of Open-Cut Type Tunnel in Transverse Direction
2. Design Example of Shield-driving Tunnel which is constructed at Changing Site of Ground Condition
3. Design Example of Shield-driving Tunnel which is constructed under the Retaining Caisson
4. Design Example of Connecting Section between Shaft and Tunnel

Reference Materials
1. Mechanical Properties of Isolation Materials
2. Construction Methods of Shield Tunnels with Isolation Design
3. Construction Methods of Open-Cut Type Tunnels with Isolation Design
4. Applicability of Seismic Isolation Design for Longitudinal Direction of Underground Structures
5. Applicability of Seismic Isolation Design for Transverse Direction of Open-Cut Type Tunnels
6. Applicability of Seismic Isolation Design for Transverse Direction of Shield driving Tunnels
7. Applicability of Seismic Isolation Design for Connection section between Shaft and Tunnels
8. Applicability of Analysis Methods in Longitudinal Direction of Underground Structures with Isolation Design
9. Applicability of Analysis Methods in Transverse Direction of Underground Structures with Isolation Design
10. Analysis Examples of Settlement of Surrounding Soils around Underground Structures with Isolation design
11. Verification Tests Results of Effectiveness of Seismic Isolation Design of Underground Structures
12. Verification Tests Results of Effectiveness of Seismic Isolation design of Underground Structures

**4.2 Basic Principle of Seismic Isolation Design**

In the draft design manual, the basic principle of the seismic isolation design is specified as follows:

(1) The objective of the seismic isolation design for the underground structures is to decrease the section forces developed during earthquakes

(2) The thickness and the length of the isolation layer shall be designed so as to get the effective isolation function.

(3) When the seismic isolation systems are employed, the stability during the construction

and the stability against the usual loads shall be verified.

(4) In the seismic isolation design, the two type of earthquake ground motion shall be taken into account. They are the earthquake ground motion with high probability to occur during the lifetime of the structures and the earthquakes ground motion with strong intensity and the low probability to occur during the lifetime of the structures. Against these two types of earthquake ground motions, the underground structures shall be designed to insure the seismic performance level depending on the structural characteristics, purposes of use, importance, etc.

(5) Seismic isolation systems are applied both for the transverse and longitudinal directions of the underground structures. In the transverse direction, the earthquake response is analyzed by using Finite Element Method (FEM) model where the inertia force of ground is applied to the model. In the longitudinal direction, the earthquake response is analyzed using beam-spring model where the deformation of the ground applied is analyzed through the dynamic analysis of the ground. In the analysis of the connection of the shaft and the tunnels, the beam-spring model or axisymmetric FEM model. The properties of soils and structures shall be given appropriately depending on the response level.

(6) In the design of the underground structures with complicated vibrational characteristics during earthquakes, the safety shall be check by using detailed model and analysis methods.

(7) Isolation materials shall be selected considering the constructionablity, watertightness, durability, material properties, etc., and shall be used in the reliable range of the material properties.

## 5. CONCLUDING REMARKS

The preceding pages presented an outline of 3-year joint research program on seismic isolation systems for underground structures to improve the structural performance and the safety during earthquakes. There is an idea of the seismic isolation system for the underground structures long time ago, but the isolation materials and the construction methods applicable for the systems had not yet been developed. Through the joint research program, 5 kinds of seismic isolation materials have been developed and the analysis and design methods for the underground structures with the seismic isolation systems have been also studied and developed. The final accomplishment is complied as a "Draft Manual for Seismic Isolation Design of Underground Structures". Since the draft manual is now under printing, it will be available in around June.

This research is one of the first steps to realize a new earthquake resistant structure. We are planning to study furthermore about the practical application of the isolation systems and the verification tests using full-scale structures should be studied.

## ACKNOWLEDGMENTS

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6) Tanaka, T, and Suzuki, T : Research and : Development on the Seismic Isolation Systems applied to Urban Tunnels (Part-1: Effects of Seismic Isolation and Seismic design), 7th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, November 4-7, 1997, Seattle, Washington

**Table 1** Seismic Isolation Materials Developed

| Construction Methods | Isolation Material | Material Contents |
|---|---|---|
| Shield Driving Tunnel | Asphalt-based Material | Asphalt and portland cement with high-water absorbing polymer |
| | Urethan-based Material | Urethan with fly ash and polyor |
| | Silicon-based Material | Silicon oil and fly ash with polyether |
| Open-Cut Type Tunnel | Liquid Rubber Material | Polybutadiene-type liquid rubber with polyisocyanate |
| | Precast Rubber Panel | Rubber tips made of shredded tires with urethan polymer resin |

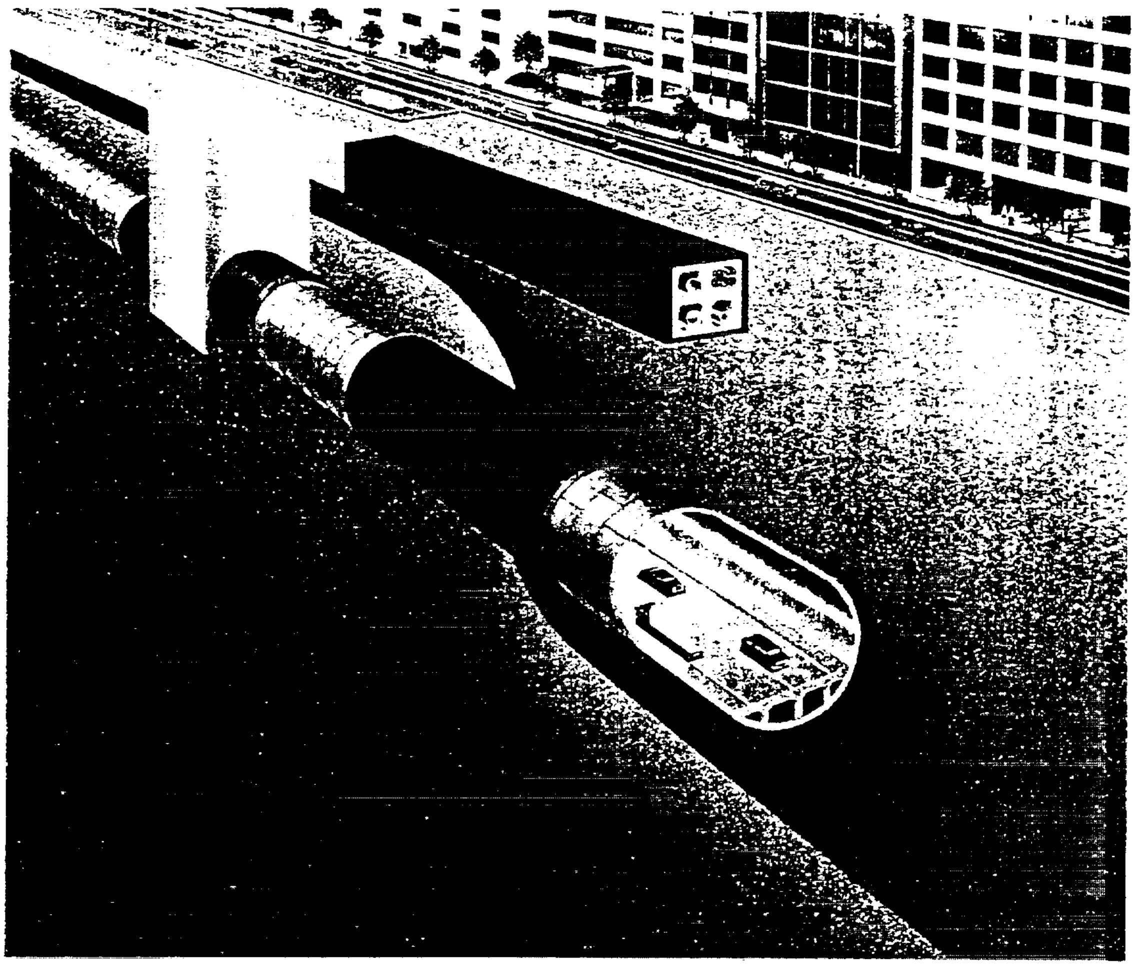
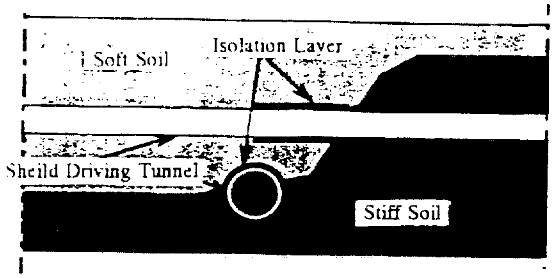
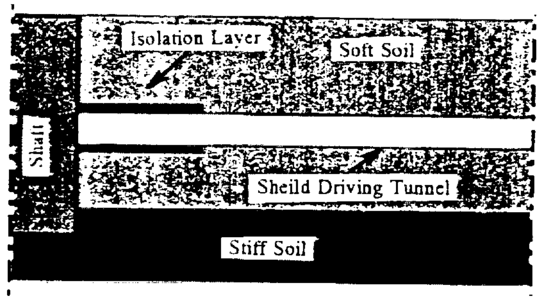


**Fig.1** Concept of Seismic Isolation Systems for Underground Structures

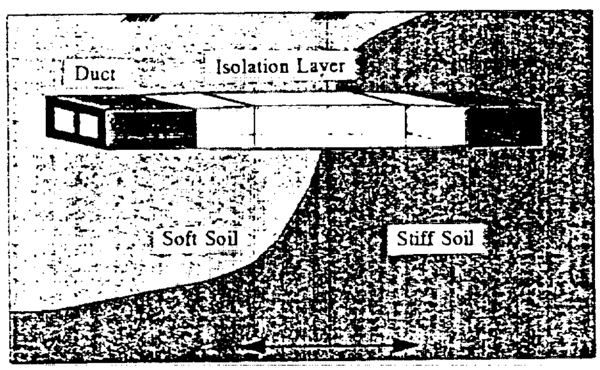



(1) Boundary of the Change of Ground Condition

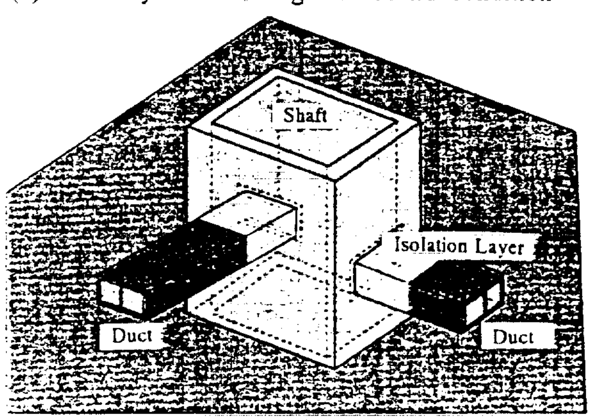



(2) Connection between Shaft and Tunnel

(a) Shield Driving Tunnels



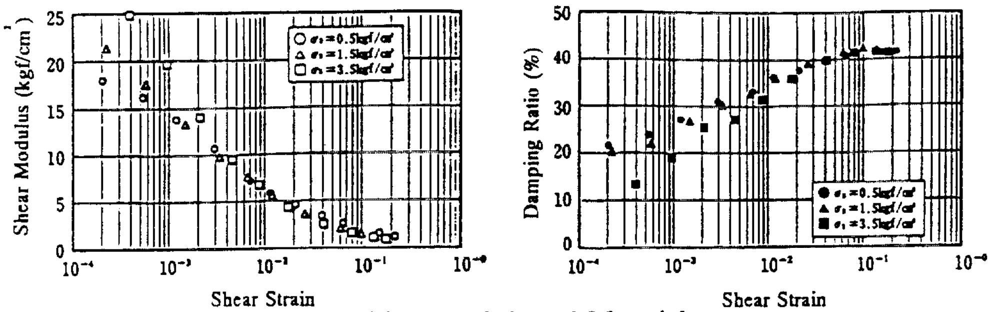

(1) Boundary of the Change of Ground Condition



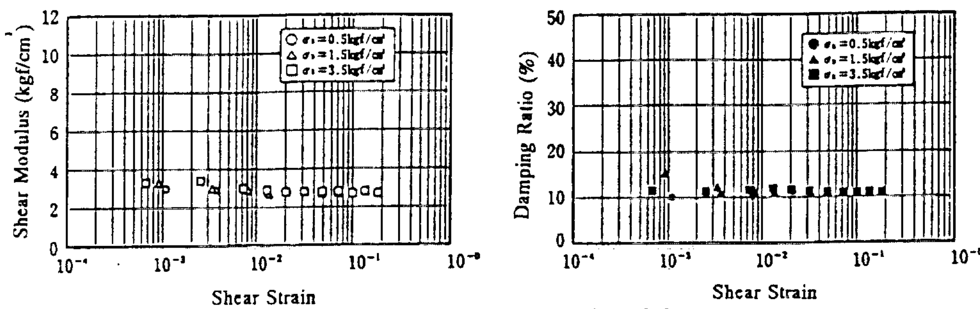

(2) Connection between Shaft and Tunnel

(b) Open-Cut Type Tunnels

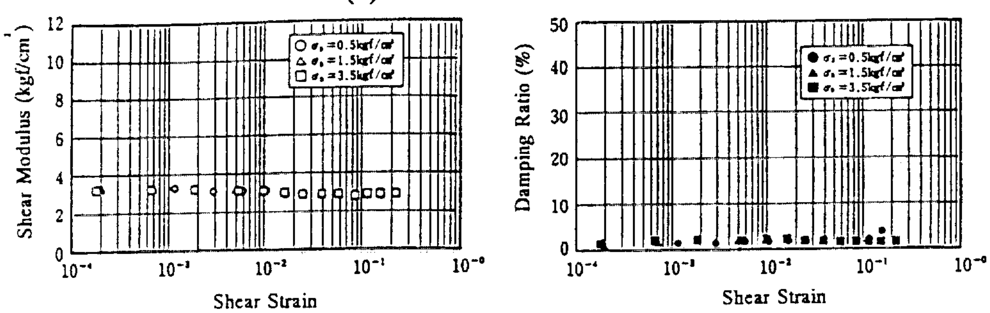
Fig.2 Application of Seismic Isolation Systems



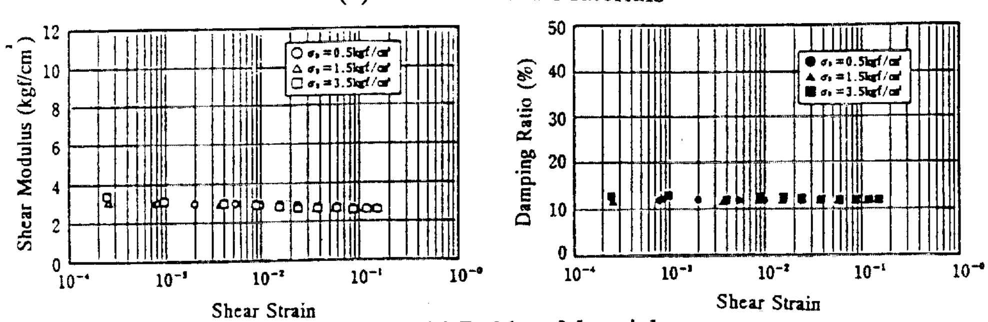

(a) Asphalt-based Material



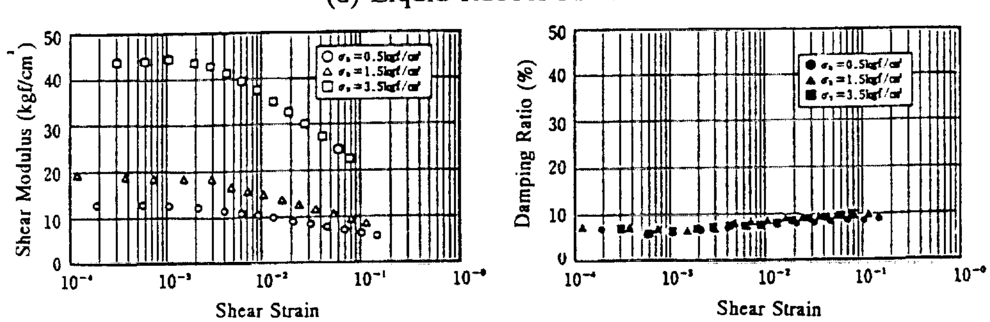

(b) Urethan-based Materials




(c) Silicon-based Materials

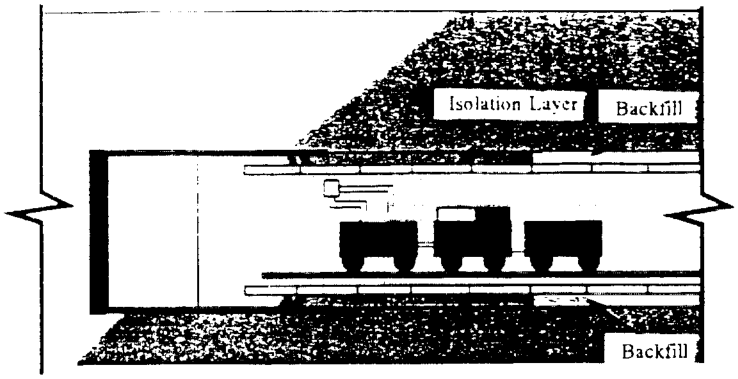



(d) Liquid Rubber Materials

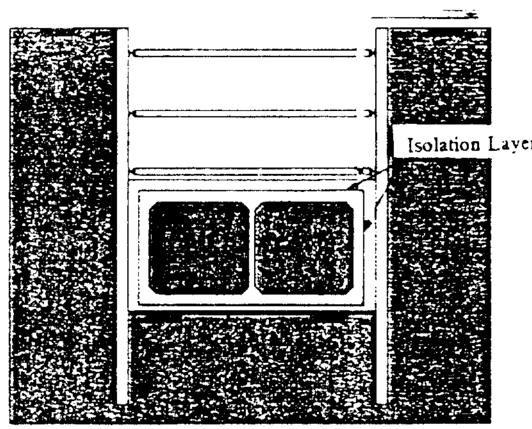



(e)Precast Rubber Panel

**Fig.3** Dynamic Mechanical Properties of Seismic Isolation Materials Developed




(a) Shield Driving Tunnels




(b) Open-Cut Type Tunnels

Fig.4 Outline of Construction Methods

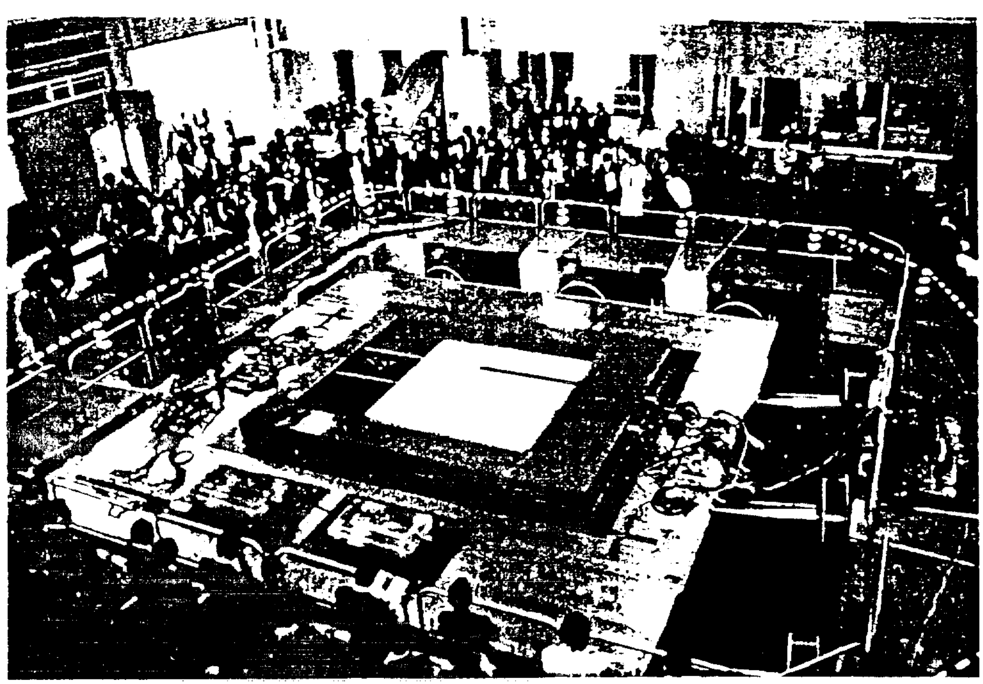
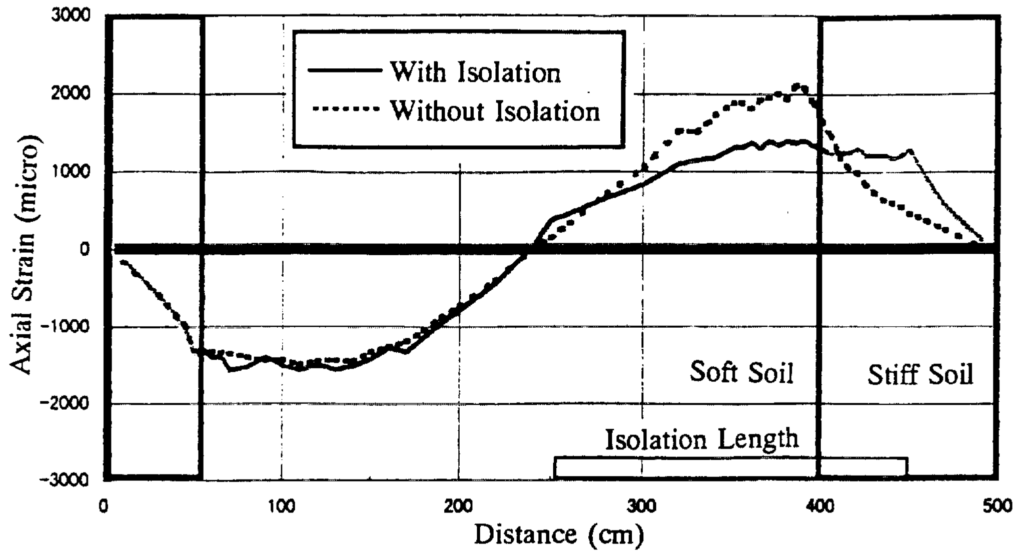
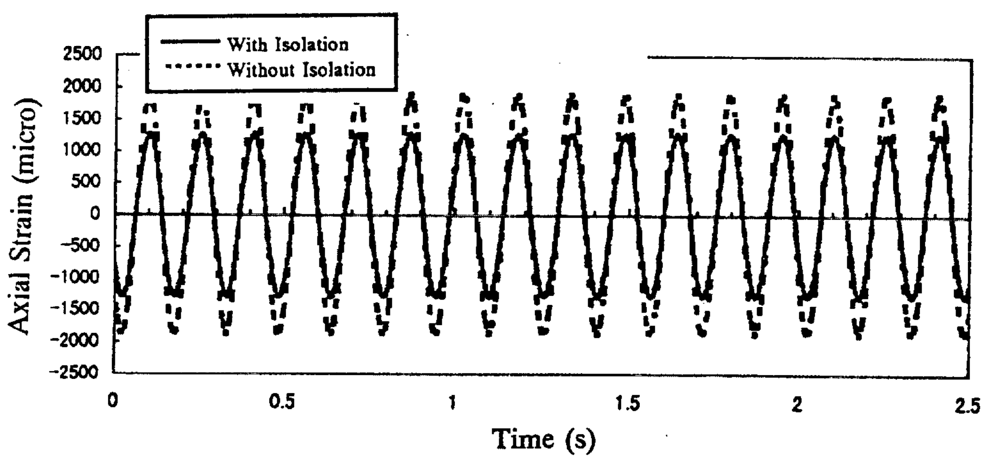


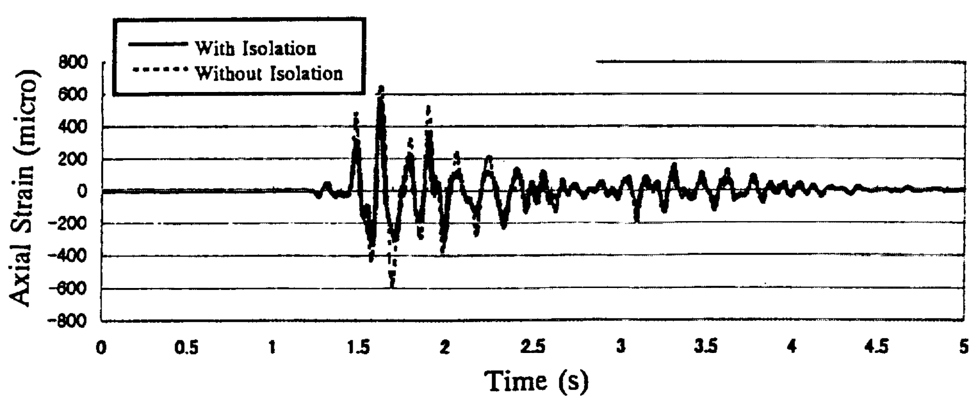
Fig.5 Model for Shake Table Tests




(a) Strain Distribution in Tunnel Model in The Longitudinal Direction
(Sinusoidal Input : 6.5Hz, 150gal)




(b) Strain Response
(Sinusoidal Input : 6.5Hz, 150gal)




(c) Strain Response (Earthquake Wave)

**Fig.6** Test Results of Shake Table Tests